

EFFECT OF MANUFACTURING ERRORS ON FIELD QUALITY  
OF THE LBL SSC DIPOLES\*

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## Summary

A method is developed for determining the field aberrations resulting from specific kinds of manufacturing errors. This method is applied to the 40-mm i.d. dipoles under consideration at LBL, and also to similar ones with 30 and 50 mm i.d. The method is also applied to the CBA and Doubler/Saver magnets and the results compared with the measurements. The results obtained by this method are also compared with those obtained by assigning identical errors to the positions of the edges of all the coil sectors.

## Introduction

Figure 1 shows a cross section of the kind of magnet under consideration.

The coil cross section is represented by a group of cylindrical sectors (which we call "blocks" out of habit) with the current density varying as  $1/r$ , and independent of  $\theta$ , within each sector (Fig. 2). For this model the field multipole coefficients (defined later) can be determined analytically, along with their partial derivatives with respect to  $r_1$ ,  $r_2$ ,  $\theta_1$ , and  $\theta_2$ , of each sector.<sup>(1)</sup>

The effect of manufacturing errors on field quality is determined in the following way:

We identify, in terms that are meaningful to magnet designers and manufacturers, the kinds of dimensional errors that can occur in coil manufacture, and we assign numerical values to them. These manufacturing errors can be expressed as combinations of variations of  $r_1$ ,  $r_2$ ,  $\theta_1$ , and  $\theta_2$  of the various blocks. Then, using the partial derivatives, we calculate the effects of the manufacturing errors on the field multipole coefficients. Finally we combine, in rms fashion, the effects of all of the manufacturing errors upon each field multipole coefficient.

## Field Representation

We represent the magnetic field in the magnet aperture in terms of multipole coefficients

$$c_n = a_n + ib_n$$

where  $n$  is the number of pole pairs associated with a particular field aberration (dipole,  $n = 1$ ; quadrupole,  $n = 2$ , etc. Note that this nomenclature is different from that used by some others). The term  $a_n$  represents a "skew" component ( $B_y = 0$  for  $y = 0$ ), while  $b_n$  represents a "non-skew" component ( $B_x = 0$  for  $y = 0$ ). The magnitude of the multipole coefficient is the magnitude of the corresponding field component at an arbitrary normalizing radius  $\rho$ , which we take as 10 mm in this study. The field, then, can be represented by the equation

$$B^* = B_x - iB_y = \sum_{n=1} c_n (z/\rho)^{n-1}, \text{ where } z = x + iy$$

## Application to LBL 40-mm I.D. Dipoles

### Coil Dimensions

In this study, we use the dimensions given in Table 1. This represents a rough approximation to the proposed SSC dipoles under development by LBL.

Table 1

Layer	No. of conductors	Coil Dimensions			
		$r_1$ (mm)	$r_2$ (mm)	$a_1$ (deg.)	$a_2$ (deg.)
1	17	20.00	29.37	0	76.855
2	18	29.97	38.61	0	42.120

The current is the same in both layers.

### Relation Between Manufacturing Errors and Block Dimensional Errors

These relationships are presented in Tables 2 and 3.

Table 2 shows how a particular manufacturing angular error,  $\epsilon$ , affects the angles  $\theta_1$ , and  $\theta_2$  in each quadrant. For example, if the upper pole piece is off center by an angle  $\epsilon$  in the ccw direction (code A11), then in quadrants 1, 2, 3, and 4 respectively,  $\theta_1$  is increased by amounts  $1/2 \epsilon$ ,  $-1/2 \epsilon$ ,  $1/2 \epsilon$ , and  $-1/2 \epsilon$ , and  $\theta_2$  is increased by amounts  $\epsilon$ ,  $-\epsilon$ ,  $0$ ,  $0$ . Since this error can occur in either the top or bottom pole piece we say there are two "occurrences", and we add the effect twice in calculating the rms values of the multipole coefficients. This error could apply to either the inner or the outer layer independently, or to both layers collectively.

Table 3 shows similar data for radial position errors. Conceivably the errors could occur in each quadrant independently, in all four quadrants collectively, or in pairs of quadrants with various signs. Only the most likely combinations have been listed.

### Manufacturing Errors; Numerical Values

These are presented in Tables 4 and 5 for azimuthal and radial errors, respectively.

In Table 4, the "case" designation corresponds to the "code" designation of Table 2, with the addition of a 1, 2, or 3 to designate, respectively, the inner layer only, the outer layer only, or both layers.

The details of the calculation of the effect of a difference in the elastic modulus are not presented here. It is assumed that the nominal elastic modulus is  $2 \times 10^6$  psi, the precompression hoop stress is 20,000 psi, and the elastic moduli of the upper and lower halves differ by  $\pm 5\%$  from the nominal value.

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Table 2  
Azimuthal Error Relationships

Code		Multipliers of $\epsilon$								Number of Occurrences
		$\Delta\theta_1$				$\Delta\theta_2$				
		Quadrant				Quadrant				
		1	2	3	4	1	2	3	4	
A11	Upper pole piece off center by angle $\epsilon$ , ccw	$+\frac{1}{2}$	$-\frac{1}{2}$	$+\frac{1}{2}$	$-\frac{1}{2}$	+1	-1	0	0	2
A21	Upper pole piece too wide by angle $\epsilon$ on each side	$-\frac{1}{2}$	$-\frac{1}{2}$	$+\frac{1}{2}$	$+\frac{1}{2}$	-1	-1	0	0	2
A35	Joints between upper and lower coil above horizontal centerline by angular amount $\epsilon$	+1	+1	-1	-1	0	0	0	0	2

Table 3  
Radial Error Relationships

Code	Description	Multipliers of $\epsilon$				Quadrants affected for one occurrence	Number of occurrences
		$\Delta r_1$	$\Delta r_2$	$\Delta r_1$	$\Delta r_2$		
R111	Upper half of inner coil too thick by amount $\epsilon$	-1	0	0	0	1, 2	2
R112	Upper half of outer coil too thick by amount $\epsilon$	-1	-1	-1	0	1, 2	2
R31	Radial distance between coils too small by amount $\epsilon$	+1	+1	0	0	1, 2, 3, 4	1
R41	Outer radius of outer coil displaced outward by amount $\epsilon$	+1	+1	+1	+1	1	4
R42	Same as R41	+1	+1	+1	+1	1, 2, 3, 4	1

Table 4  
Azimuthal Manufacturing Errors

Serial No.		Case	Multiplier, radians	No. of Occurrences
Pole Piece Centering				
1	Fit of key in keyway			
	Both layers: .001" at r = 42.0 mm	A113	$6.05 \times 10^{-4}$	2
	Thickness of pole-piece-to-coil insul.			
2	Inner layer: .0005" at r = 24.7 mm	A111	$5.14 \times 10^{-4}$	2
3	Outer layer: .0005" at r = 34.3 mm	A112	$3.70 \times 10^{-4}$	2
Die and punching tolerances				
4	Inner layer: .0005" at r = 24.7 mm	A111	$5.14 \times 10^{-4}$	2
5	Outer layer: .0005" at r = 34.3 mm	A112	$3.70 \times 10^{-4}$	2
Pole Piece Width				
	Thickness of pole-piece-to-coil insul.			
6	Inner layer: .0005" at r = 24.7 mm	A211	$5.14 \times 10^{-4}$	2
7	Outer layer: .0005" at r = 34.3 mm	A212	$3.70 \times 10^{-4}$	2
Die and punching tolerances				
8	Inner layer: .0005" at r = 24.7 mm	A211	$5.14 \times 10^{-4}$	2
9	Outer layer: .0005" at r = 34.3 mm	A212	$3.70 \times 10^{-4}$	2
Midplane Registration				
	Elastic modulus (difference, top to bottom)			
10	Inner layer: $\pm 5\%$	A351	$6.7 \times 10^{-4}$	1
11	Outer layer: $\pm 5\%$	A352	$3.7 \times 10^{-4}$	1
	Azimuthal width of coil (difference, top to bottom)			
12	Inner layer: .002" at r = 24.7 mm	A351	$20.6 \times 10^{-4}$	1
13	Outer layer: .002" at r = 34.3 mm	A352	$14.8 \times 10^{-4}$	1

Table 5  
Radial Manufacturing Errors

Serial No.		Code	Multiplier, inches/meters	No. of Occurrences
Pole piece centering				
Layer thickness				
14	Inner layer:	R111	$.002/5.08 \times 10^{-5}$	2
15	Outer layer:	R112	$.002/5.08 \times 10^{-5}$	2
16	Interlayer insul. thickness	R31	$.0005/1.27 \times 10^{-5}$	1
Coil-to-iron insul. thickness				
17	Different for each quadrant	R41	$.0005/1.27 \times 10^{-5}$	4
18	Same for all quadrants	R42	$.0005/1.27 \times 10^{-5}$	1
19	Diameter of hole in iron	R42	$.0005/1.27 \times 10^{-5}$	1

### Effects of Individual Manufacturing Errors on Multipole Coefficients

These are presented in Tables 6 and 7, respectively, for azimuthal and radial errors.

### Combined Effects of Manufacturing Errors on Multipole Coefficients

These are presented in Table 8.

### Effect of Coil Inside Diameter on Field Quality

Table 8 shows results for LBL-type magnets of 30 and 50 mm i.d., in addition to the proposed 40-mm-i.d. design. For these magnets, all radii have been decreased or increased by 5 mm, while coil thicknesses, coil-to-iron spacing, and block edge angles have been maintained. The manufacturing errors used are the same as those of the 40-mm-i.d. design; they have not been scaled in proportion to the coil diameter.

There are no surprises; the results are about what one would get by simply scaling with coil average radius.

Table 6

Effects of Individual Manufacturing Errors on Field Quality:  
Azimuthal Errors

				Normalized multipole coefficients					
Serial No.	Case		Real or Imaginary	$\frac{\Delta C_1}{C_1}$ $\times 10^4$	$\frac{\Delta C_2}{C_1}$ $\times 10^4$	$\frac{\Delta C_3}{C_1}$ $\times 10^4$	$\frac{\Delta C_4}{C_1}$ $\times 10^4$	$\frac{\Delta C_5}{C_1}$ $\times 10^4$	$\frac{\Delta C_6}{C_1}$ $\times 10^4$
1	A11 <sub>3</sub>	Fit of key in keyway	R I	6.05 0	0 1.50	< .01 0	0 .04	.01 0	0 .01
		Thickness of pole-piece-to-coil insulation:							
2	A11 <sub>1</sub>	Inner layer	R	2.33	0	.25	0	.02	0
3	A11 <sub>2</sub>	Outer layer	I R I	0 2.02 0	.98 0 .21	0 .17 0	.11 0 .06	0 < .01 0	< .01 0 <.01
		Punching tolerance:							
4	A11 <sub>1</sub>	Inner layer	R	Same as above					
5	A11 <sub>2</sub>	Outer layer	I R I						
		Thickness of pole-piece-to-coil insulation:							
6	A21 <sub>1</sub>	Inner layer	R	0	.37	0	.10	0	.02
7	A21 <sub>2</sub>	Outer layer	I R I	2.59 0 .75	0 .79 0	.09 0 .17	0 .01 0	.05 0 .01	0 < .01 0
		Punching tolerance:							
8	A21 <sub>1</sub>	Inner layer	R	Same as above					
9	A21 <sub>2</sub>	Outer layer	I R I						
		Elastic modulus tolerance:							
10	A35 <sub>1</sub>	Inner layer	R	0	1.37	0	.02	0	< .01
11	A35 <sub>2</sub>	Outer layer	I R I	0 0 0	0 .26 0	0 0 0	0 .02 0	0 0 0	0 < .01 0
		Azimuthal coil width:							
12	A35 <sub>1</sub>	Inner layer	R	0	4.20	0	.07	0	.03
13	A35 <sub>2</sub>	Outer layer	I R I	0 0 0	0 1.05 0	0 0 0	0 .09 0	0 0 0	0 < .01 0

Table 7

Effects of Individual Manufacturing Errors on Field Quality:  
Radial Errors

Normalized multipole coefficients

Serial No.	Case		Real or Imaginary	$\frac{\Delta C_1}{C_1}$ $\times 10^4$	$\frac{\Delta C_2}{C_1}$ $\times 10^4$	$\frac{\Delta C_3}{C_1}$ $\times 10^4$	$\frac{\Delta C_4}{C_1}$ $\times 10^4$	$\frac{\Delta C_5}{C_1}$ $\times 10^4$	$\frac{\Delta C_6}{C_1}$ $\times 10^4$
Layer thickness tol.									
14	R11 <sub>1</sub>	Inner layer	R	0	2.99	0	.14	0	.09
			I	2.60	0	.59	0	.01	0
15	R11 <sub>2</sub>	Outer layer	R	0	5.42	0	.38	0	.14
			I	5.12	0	.73	0	.08	0
Interlayer insulation thickness									
16	R31		R	0	0	0	0	0	0
			I	1.1	0	.23	0	.02	0
Coil-to-iron insulation thickness									
17	R41	Different in each quadrant	R	.97	1.42	.64	.12	.03	.04
			I	1.38	.51	.16	.10	.02	.02
18	R42	Same in all quadrants	R	0	0	0	0	0	0
			I	1.4	0	.16	0	.02	0
19	R42	Radius of hole in iron	R	Same as Serial No. 18					
			I						

Table 8

## Combined Effects of Manufacturing Errors on Field Quality

RMS values of multipole coefficients, normalized to nominal dipole field						
multipole order n(1)	Real, a <sub>n</sub> (skew)			Imaginary, b <sub>n</sub> (non-skew)		
	Coil inside diameter, mm					
	30	40	50	30	40	50
2	13. E-4	7.906E-4	5.2E-4	3.2E-4	2.134E-4	1.6E-4
3	16. E-5	7.655E-5	4.3E-5	2.3E-4	1.042E-4	.6E-4
4	12. E-5	4.621E-5	2.2E-5	5.6E-5	2.117E-5	1.0E-5
5	15. E-6	4.474E-6	1.8E-6	4.9E-5	1.306E-5	.5E-5
6	8.1E-5	1.719E-5	.5E-5	14. E-6	2.938E-6	.9E-5
7	15. E-6	2.390E-6	.6E-6	9. E-6	1.522E-6	.4E-6
8	29. E-6	3.427E-6	.7E-6	42. E-7	5.211E-7	1.0E-7
9	18. E-7	1.813E-7	.3E-7	73. E-7	6.564E-7	1.0E-7
10	31. E-7	2.165E-7	.3E-7	1.294E-7	1.294E-7	.2E-7

Normalizing radius = 10 mm

(1)<sub>1</sub> = dipole, 2 = quadrupole, etc.Application of the Method to CBA  
and Doubler/Saver Magnets

The method presented here has been applied to the CBA and Doubler/Saver dipoles. The numerical values for the manufacturing errors are the same as those used for the LBL magnets; they are not scaled to the magnet size.

A certain amount of fudging had to be done in the interest of saving time. For example, the CBA magnets have two blocks per layer; the representation used here was one block per layer with the Doubler/Saver block angles.

The calculated results, together with experimental results from Erich Willen's paper(2), are presented in Tables 9A and 9B.

Except for the quadrupole terms for the Doubler/Saver magnets, the agreement is remarkably good, considering that the inputted data for the manufacturing errors were simply educated guesses. The quad terms are turned out by shimming so the disagreement is understandable.

#### Comparison of Two Methods for Field-Aberration Calculation

For the 40-mm-i.d. LBL magnet, we also calculate the field aberrations by the following simpler method: Each of the four edges of each of the eight blocks is assigned an error (the same value for all edges). There is no simple relation between such errors and the manufacturing errors, and the conditions of compatibility of the errors is violated. Nevertheless it is a useful method, and a comparison with the method of this report is of interest. The comparison of the results of the two methods is presented in Table 10. The results were fudged to make the rms sums of both the  $a_n$  and  $b_n$  terms the same for the two methods, which corresponds to an error in all block edge positions of 0.0018 inches.

About all that can be said of the results for certain is that they are different, by as much as a factor of 5 for some components.

#### Conclusions

The identification of manufacturing errors, and the assignment of numerical values to those errors, are the result of "educated guesses" by the author, and of course the accuracy of the final results is directly affected by those errors. Obviously, those numbers should be refined.

The method used here identifies particular field aberration effects with particular manufacturing errors, and can therefore serve as a basis for specifying tolerances, or altering the design or manufacturing methods. Simply making everything "as good as possible" or "to one mil" might be prohibitively expensive.

Table 9A

#### Comparison of Calculated and Measured Field Aberrations: CBA Dipoles

n	$a_n$		$b_n$	
	Calc.	Meas.	Calc.	Meas.
2	9.1E-5	> 5.0E-5	3.6E-5	> 2.0E-5
3	3.8E-6	≅ 3.1E-6	2.9E-6	< 8.8E-6
4	9.9E-7	≅ 9.4E-7	3.6E-7	≅ 3.5E-7
5	2.2E-8	< 8.0E-8	5.7E-8	> 2.7E-7
6	2.2E-8	≅ 2.4E-8	5.1E-9	< 1.8E-8
7	1.6E-9	< 4.1E-9	1.5E-9	< 4.1E-9
8	8.2E-10	--	1.4E-10	--
9	3.2E-11	--	6.9E-11	--
10	2.6E-13	--	5.2E-12	--

Table 9B

#### Comparison of Calculated and Measured Field Aberrations: Doubler/Saver Dipoles

n	$a_n$		$b_n$	
	Calc.	Meas.	Calc.	Meas.
2	3.8E-4	>> 2.0E-5	7.2E-4	>> 1.9E-5
3	2.4E-5	> 1.8E-5	1.1E-4	< 4.8E-5
4	1.1E-5	≅ 8.9E-6	1.9E-5	> 4.7E-6
5	4.1E-7	< 1.1E-6	2.7E-6	≅ 3.2E-6
6	6.4E-7	≅ 5.2E-7	7.7E-7	< 3.0E-7
7	7.1E-8	>> 1.1E-8	1.1E-7	< 2.0E-7
8	6.6E-8	> 3.8E-8	7.6E-8	> 2.5E-8
9	4.2E-9	< 2.4E-8	1.2E-8	> 1.9E-9
10	5.4E-9	< 8.6E-9	9.2E-9	> 5.3E-9

Table 10

#### Comparison of Two Methods for Calculating Effect of Dimensional Errors on Field Aberrations

n	$a_n$ (real)		$b_n$ (imag.)	
	method*		method*	
	1	2	1	2
2	7.9E-4	6.0E-4	2.1E-4	4.7E-4
3	7.7E-5	24. E-5	1.0E-4	1.9E-4
4	4.1E-5	5.1E-5	2.1E-5	8.4E-5
5	4.5E-6	10.9E-6	1.3E-5	2.6E-5
6	1.7E-5	1.1E-5	2.9E-6	10.7E-6
7	2.4E-6	6.8E-6	1.5E-6	5.5E-6
8	3.4E-6	2.8E-6	5.2E-7	25. E-7
9	1.8E-7	3.8E-7	6.6E-7	11.4E-7
10	2.2E-7	2.6E-7	1.3E-7	4.3E-7

\*Method 1 is the method described in the Introduction. Method 2 applies a .00181-inch error to all block boundary positions.

#### References

1. Math Backup for LBL-17050, R. Meuser, LBL Engineering Note 6208, Jan. 1984.
2. Magnetic Imperfections, Eric Willen. In these proceedings.

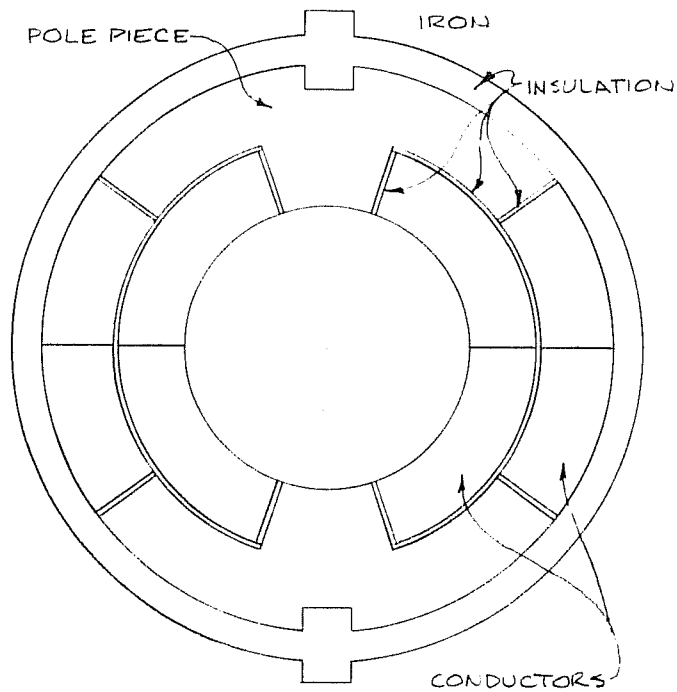


Fig. 1 Schematic cross section of LBL dipole magnet for the CBA. XBL 841-155

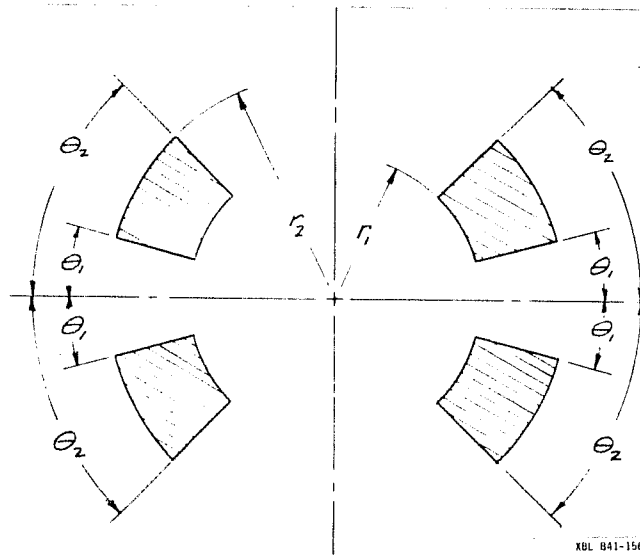


Fig. 2 Nomenclature for coil current block outline dimensions. XBL 841-156